AeroBest 2023
Lisboa, 19-21 July 2023
©ECCOMAS, Portugal

ADAPTIVE AIRBAG SYSTEMS FOR PROTECTION OF GENERAL AVIATION

Jan Holnicki-Szulc[1], Rami Faraj[1], Cezary Graczykowski[1], Grzegorz Mikułowski[1], Piotr Pawłowski[1], Andrzej Świercz[1], Zbigniew Wołejsza[1], Lech Knap[2], Krzysztof Sekuła[3], Dariusz Wiącek[3]

1: Institute of Fundamental Technological Research
Polish Academy of Sciences
Pawinskiego 5B, 02-106 Warsaw, Poland
{holnicki, rfaraj, cgraczyk, gmikulow, ppawl, aswiercz, zwolejsza}@ippt.pan.pl,
http://www.ippt.pan.pl

2: Institute of Vehicles and Construction Machinery
Warsaw University of Technology
Narbutta 84, 02-524 Warsaw, Poland
Lech.Knap@pw.edu.pl, http://www.simr.pw.edu.pl

3: Adaptronica Sp. z o. o.
Szpitalna 32, 05-092 Łomianki, Poland
{krzysztof.sekula, dariusz.wiacek}@adaptronica.pl,
http://www.adaptronica.pl

Abstract *The contribution describes three innovative external airbag systems developed by the authors for the protection of flying objects during emergency landings. The first one is the AdBag system dedicated for small drones, which is designed to protect the carried equipment and prevent damages to objects or injuries to people at the crash location. The second system is external airbag designed for ultralight aircraft Skyleader 600, which provides significant reduction of touchdown velocity and deceleration levels during emergency landings, thereby improving protection of the pilot and the passengers. Finally, the last presented solution is the Spring-Drop system with specialized airbag deployment technique, which is dedicated for specialised airdrop operations where the touchdown conditions can be extremely harsh and unexpected, while protection of transported cargo is of crucial importance. Both conceptual studies, numerical simulations and experimental tests of the three proposed systems are presented and discussed.*

Keywords: External airbags, adaptive system, emergency landing, human safety

1. INTRODUCTION

Most of the flying objects of general aviation such as drones and small aircrafts are endangered of emergency situations caused by equipment failure or human error, which result in the requirement of emergency landing. Although such flying objects are typically equipped with parachute rescue systems, they usually do not provide sufficient protection of human or carried cargo in the case of emergency situations occurring at relatively low altitudes. The possible solution of this problem is application of external adaptive airbags located below the flying object, which are deployed and inflated when the situation of emergency landing is detected. During touchdown, the activation and adjustment of special vents provides proper release of gas from the airbag, resulting in efficient impact mitigation and improved level of protection of the landing object.

The design of adaptive airbags is associated with multiple theoretical and practical challenges. In general, the concept of adaptive airbags follows a more general concept of Adaptive Impact Absorption, in which the system is adapted in semi-active way to actual dynamic loading with the use of structural fuses based on smart materials [1, 2, 3]. In a specific case of adaptive airbags, the first problem is precise identification of the landing conditions, including mass, velocity components and spatial orientation of the object [4]. The second challenge is the requirement of fast deployment and inflation of the airbag in the short period of time between detection of failure and emergency landing [5]. Finally, the third problem is providing appropriate large release of the gas from the airbag during the short period of landing [6, 7]. Due to the requirement of large gas flow rates and process robustness, neither the typical electromechanical valves nor piezoelectric valves [8, 9, 10], which are successfully used in adaptive shock absorbers, can be applied. Instead, the attention is focused on standard passive vents, dedicated membrane valves [11] or semi-passive solutions [12, 13, 14]. All the above factors cause that design and construction of adaptive external airbags for emergency landing still remains challenging engineering problem.

The following part of the paper presents three different airbag systems the protection of flying objects during emergency landings developed during several years of cooperation between Institute of Fundamental Technological Research of the Polish Academy of Sciences, Adaptronica Company and Warsaw University of Technology. The Section 2 describes AdBag system dedicated for small drones, which protects the carried equipment and prevents damages at the crash location. The Section 3 presents external airbag designed for ultralight aircraft Skyleader 600, which provides significant reduction of deceleration during emergency landings. In turn, the Section 3 highlights recently developed Spring-Drop system based on specialized airbag deployment technique, which seems promising in extremely harsh landing conditions. Eventually, in the last section summarizes the achievements and draws basic conclusions regarding the proposed systems of adaptive external airbags.

2. ADBAG – ADAPTIVE AIRBAG FOR SMALL UAV

Small drones with a total mass of several kilograms are becoming increasingly popular in various applications, including aerial surveillance, airborne observation and laser scanning. The popularity of such applications increases the likelihood of the occurrence of emergency situations. Given that drones often operate over densely populated urban areas, it is necessary to ensure protection of individuals or objects on the ground, and to minimize the transmitted shock loads to the fragile electronic equipment on the drone, such as cameras, lenses, and lidars.

The developed adaptive emergency landing system is designed specifically for unmanned aerial vehicles (UAVs), but it can also be utilized for the protection of crewed aircraft and other flying objects. The proposed device comprises an airbag with at least one pre-cut vent hole, an inflation module containing a fan drive, a gas release activation module, a fault detection module, and a ground proximity detection module. The device is also equipped with a pyrotechnic charge and an igniter located on the airbag envelope in the vicinity of the pre-cut vent hole. Additionally, the device incorporates mechanical stabilizers for spatial orientation of the object positioned above the airbag, which are designed for compact folding and rapid deployment. The operation of the device involves activating and inflating the airbag upon detection of an emergency situation, pyrotechnic activation of the vent holes, and executing the landing process through controlled gas release. The proposed device ensures a stable landing of the UAV in the appropriate spatial orientation, adapts to impact conditions by activating a selected number of vent holes based on prediction of impact conditions, and effectively mitigates the impact forces during the landing process.

The initial stage of the elaboration of the Ad-Bag system was development of a dedicated airbag design method, which included application of simplified analytical models for approximate adjustment of system parameters as well as application of fully nonlinear dynamic FEM models (LS-Dyna explicit solver) for precise airbag shape design (Fig. 1). Moreover, a drop test stand with the maximal drop height of 20 m, composed of a vertical guiding system, remote release of suspended object, and a base plate with piezoelectric force transducers for measurement of total vertical loads was designed and constructed. The series of drop test conducted with the use target-shaped airbag (Fig. 2) allowed determine system dynamic response the required area of the valve for various mass and velocity of the landing object.

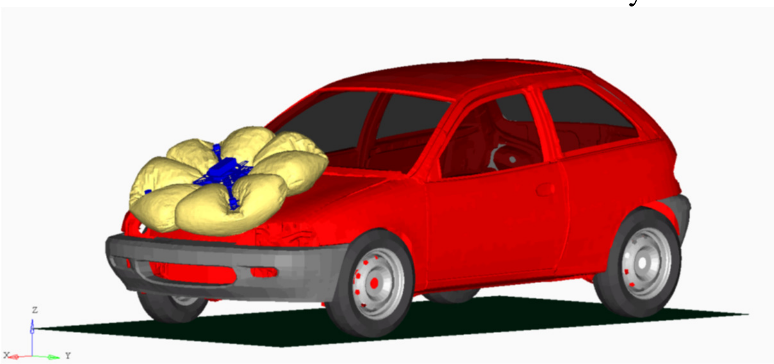

Figure 1. Visualization of the numerical finite element simulation showing emergency landing of the drone equipped with external airbag on the standard city car (numerical simulation by Mr. Krzysztof Hinc, [15]).

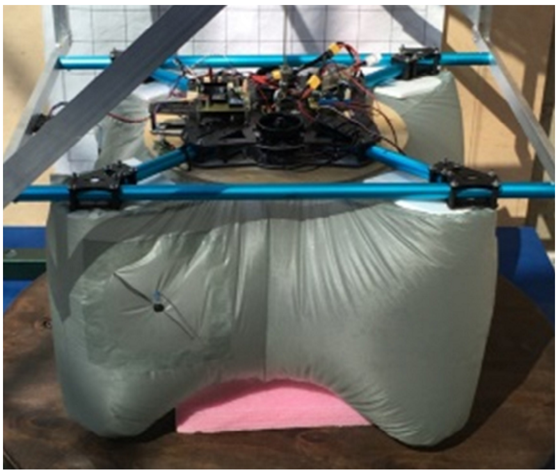

Figure 2. Complete AdBag system with a target-shaped airbag, prepared for drop tests

In the following stage of research the AdBag system has been integrated with the "Iron bird" for the free-fall testing purposes. The free-fall test were conducted in accordance to general guidelines of the project and has proved that the AdBag System demonstrator operates successfully during free-fall in field conditions. Selected frames captured by a high-speed camera during free-fall and landing are presented in Fig. 3a. Moreover, a quadcopter drone was equippped with the complete integrated AdBag system and prepared to be used in flight tests (Fig. 3b).

Ultimately, the flight tests of the developed system were conducted. During the test, the drone has achieved the height of 14.3 m. The descent speed at the moment of impact with the ground was equal 8.9 m/s. The vent holes were successfully ignited at the correct altitude. The drone impacted the ground at an angle of approximately 40 degrees, which was attributed to partial malfunction of one aerodynamic stabilizer. Nevertheless, the test demonstrated effectiveness of the AdBag system even in the case of a rotated drone during descent. After the impact with the ground with the AdBag system, the drone did not lose its flight capabilities.

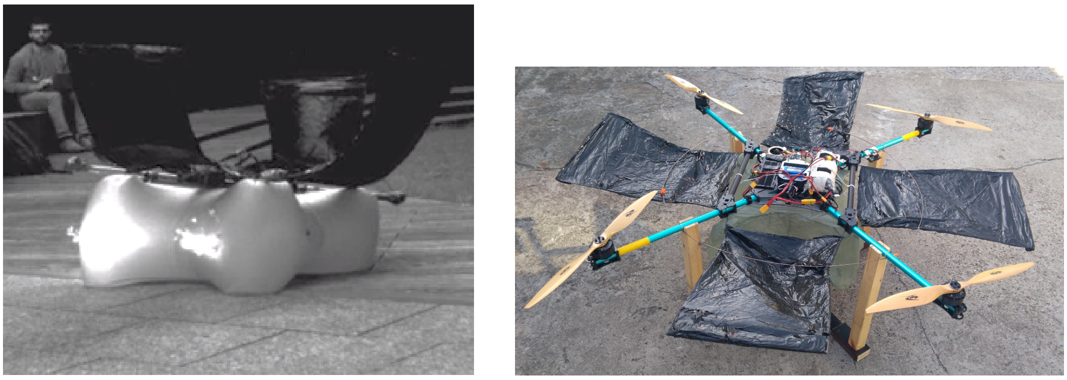

Figure 3. a) Free-fall tests of the complete AdBag system, b) drone equipped with the AdBag system and stabilizers constructed for flight testing purposes.

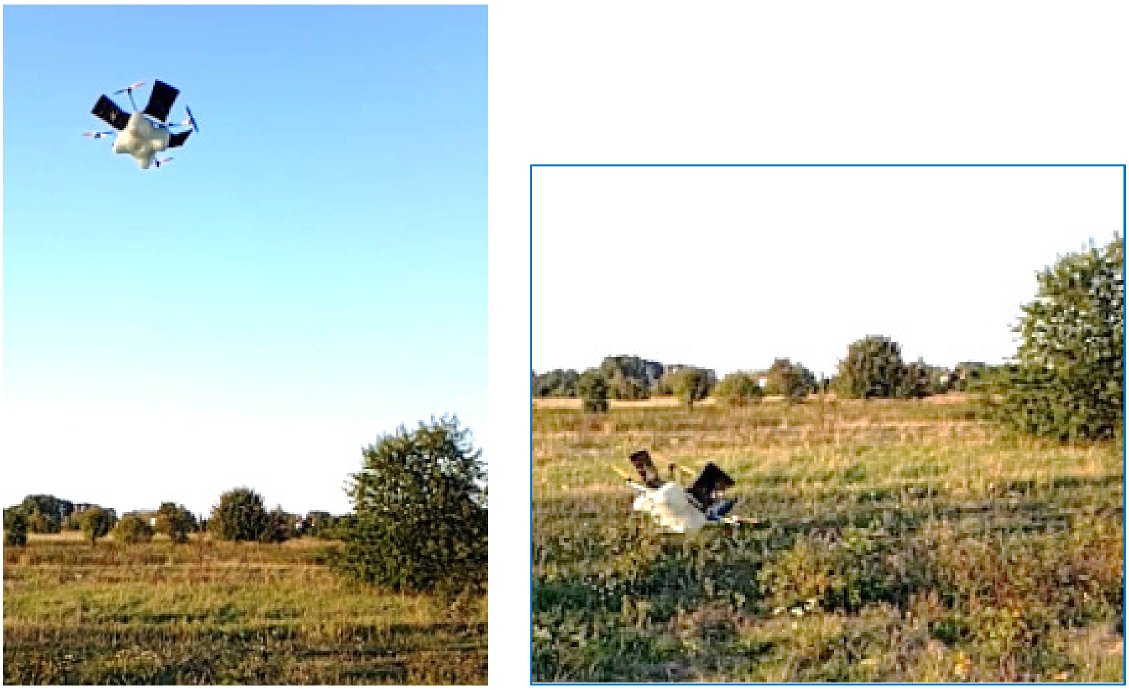

Figure 4. Results of the conducted flight test: a) free fall of the drone (propellers off, airbag inflated), b) start of the collision with the ground

Summarizing the conducted research, the AdBag System allows for the absorption of the total energy of a falling drone from an arbitrary height, with a minimum operational height of 4 m. Depending on the height at which the drone experiences a malfunction, one, two, or three vent holes are activated during collision with the ground, which provides efficient system adaptation. During both laboratory and flight tests, the AdBag System operated fully satisfactorily, provided absorption of the entire impact energy and efficient UAV protection.

3. ADAPTIVE AIRBAG FOR SKYLEADER 600 AIRCRAFT

An innovative adaptive external airbag to enhance the safety of ultralight aircraft (up to 600kg) has been developed, manufactured, and thoroughly tested within the framework of the SOFTLAND project. The fabricated prototype airbag was aimed to fulfil the following fundamental requirements set by the aircraft manufacturer:

- Possibility of using in conjunction with a parachute;
- Reduction of vertical touchdown velocity from 7.5 m/s (descent with a parachute) to 2.5 m/s;
- Limitation of the deceleration to 5 g;
- Minimal mass, up to a maximum of 15kg;
- Deployment time below 13 seconds (approx. 100 m descent with the parachute);
- No collision with the aircraft landing gear;
- Compatibility with other currently utilized aircrafts.

The capabilities of two different methods for inflating the emergency airbag were examined. In the first method, the inflation was achieved by utilizing high-performance fans, and the entire airbag volume was filled with air from the atmosphere. A significant advantage of this approach was the ability to replenish gas losses, thereby eliminating the requirement for the airbag to be completely airtight and enabling its construction through sewing technology. In turn, the second tested inflation method relied on the use of cylinders with compressed gas. In such a case, due to the limitations of system mass, it was necessary to apply solution requiring minimal gas storage. Thus, the inflated airbag had to be as small as possible and completely airtight. As constructing an airtight pneumatic structure using sewing technology proved to be highly challenging, a design consisting of two layers of fabric was proposed: an internal layer to ensure air-tightness and an external sewn layer to provide mechanical strength.

Moreover, various methods of the release of gas from the emergency landing airbag were analyzed: an active (electromagnetic) valve and a passive valve opened by gas pressure. To compare the effectiveness of both valves, the preliminary drops were performed on a model equipped with an electromagnetic valve, and compared to those obtained for a passive valve. The obtained results (braking force, braking distance, and maximal deceleration) appeared to be relatively similar and to fulfil the initial requirements. These allowed to resign from the use of active valve, which was potentially prone to failures and required power supply, in favour of a passive valve.

The proposed passive valve was automatically activated during the airbag compression process. The triggering factor was the change of internal pressure inside airbag, which caused change of airbag geometry and corresponding change of internal forces in the airbag envelope. The critical aspect of constructing a passive valve was determining the safe force level during initial airbag inflation, as well as the force level triggering the valve during the airbag compression phase.

The developed large-scale drop testing stand (Fig. 5) allowed for dropping of the objects with the size and weight of the Skyleader 600 aircraft at the required velocity of 7.5 m/s.

The stand was equipped with systems for measurement of pressure inside the airbag as well as accelerations and displacements at selected locations of the aircraft. In particular, acceleration measurements were performed using accelerometers installed on the rigid components of the model aircraft. The drop tests were conducted using the Skyleader 600 model aircraft provided by the aircraft manufacturer, Zall Jihlavan Airplanes, and constructed according to the specifications of Adaptronica company. The applied model faithfully replicated the geometry and dimensions of the lower part of the Skyleader 600 aircraft.

Figure 5. Drop tests conducted at the experimental stand

The total of 31 full-scale drop tests were conducted, including 21 tests with the model aircraft. The drop height was chosen to achieve a vertical velocity of 7.5 m/s at the moment of the contact of the emergency landing airbag's with the ground. During testing, the following various characteristics and parameters of the airbag were taken into account:

- Airbag size (volumes ranging from 3-5 m^3);
- Airbag shape (cylindrical, rectangular, rosette-shaped);
- Airbag inflation method (an electric fan, compressed air cylinder, hybrid solution combining both methods).

The results obtained from the subsequent drop tests were used to verify the functioning of each analyzed design type of the SOFTLAND system. In particular, the change of object's velocity and acceleration in terms of distance to the ground was presented in Fig. 6. It can be observed that after landing the object's velocity drops below 1.5 m/s, which is lower than the required safety level equal to 2.5 m/s (Fig. 6a). Moreover, the deceleration of the landing object exceeds safety level of 5 g only during a very short period of the landing process (Fig. 6b). Finally, the obtained deceleration-displacement characteristics remains relatively flat during the entire process, which confirms high efficiency of the energy absorption.

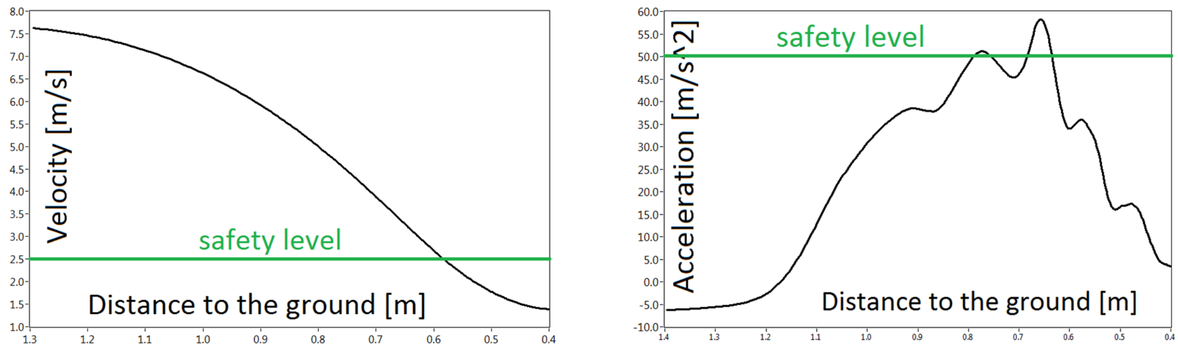

Figure 6. Measurements recorded during the drop test: a. object velocity as a function of distance to the ground, b. object acceleration as a function of distance to the ground

In the subsequent phase of the project, the engineers involved in the development of the Softland system visited several times the Zall Jihlavan Airplanes factory in Czech Republic. During these visits, the system of adaptive airbag was installed on Skyleader airplane (Fig. 7a). The verification tests proved proper system operation, including fast deployment and inflation of the air airbag in industrial conditions (Fig. 7b).

Figure 7. The Softland system installed on the aircraft: a. airbag in the closed state, b. airbag in the open state

The flight test was conducted at the Milovice Airport in the Czech Republic. The helicopter lifted the Skyleader aircraft equipped with the parachute and Softland system to an altitude of approx. 400 meters (Fig. 8a). When the operator released the attachment, the parachute opened and Softland system was deployed correctly. Unfortunately, the ropes suspending the aircraft were improperly attached, resulting in a landing with a significant vertical rotation angle. As a result, the front part of the aircraft absorbed the energy from the initial impact. Nevertheless, the Softland system absorbed the impact energy in the second stage of the process, protecting the aircraft from further damage.

From the perspective of evaluating the Softland system, the following aspects of the airbag's operation were positively verified:

- Effective initiation of the safety system by deploying the parachute from the compartment located behind the cockpit;
- Proper time instant of initiating the deployment of the airbag;
- Proper time required for the airbag deployment under aerodynamic flow conditions (suitable for an aircraft descending with a parachute);
- Correct shape of the airbag after deployment under aerodynamic resistance.

Figure 8. View of the aircraft equipped with the Softland system during a flight test

The effectiveness of energy absorption during the aircraft's collision with the ground was very hard to assess due to the abnormal course of the final phase of the experiment. Nevertheless, the measured maximum acceleration of the aircraft structure was below 5 g, which perfectly fits within the initial requirements of the project.

4. ADAPTIVE AIR-DROP SYSTEM

New systems for specialized airdrop operations are continuously being developed and utilized in military, commercial and rescue applications. Each application entails specific requirements concerning system design and performance. Furthermore, landing conditions can vary significantly, necessitating the airdrop system to be adaptable to various impact scenarios. This section discusses the development of a novel, versatile airdrop system that achieves high performance by an innovative construction and deployment mechanism. The proposed system ensures efficient impact mitigation during touchdown and enables effective safeguard of the transported cargo, particularly in scenarios in which the drop height remains relatively low.

According to the proposed concept, the capsule consists of a base with openings and cylindrical pneumatic chamber attached from its underside. The pneumatic chamber contains a stabilizing telescopic system, which maintains the shape of the pneumatic chamber. The telescopic system is equipped with a specially designed tensioning structure, which effectively supports system deployment but does not hamper its compression during landing and effectiveness of the impact absorption process. The detailed specific features of the system are currently being developed and patent claims are being prepared.

The objective of the preliminary tests is to assess the free fall speed of the device, which has a fixed mass of 2 kg and is equipped with a parachute. These tests aim to provide information regarding the time needed for object's velocity to stabilize and the value of constant free-fall velocity. Such information is required for computation of the amount of kinetic energy that has to be dissipated during touchdown.

The research team conducted a total of 5 tests involving the dropping of the capsule from 3 different heights: 4m (1 attempt), 8m (1 attempt), and 25m (3 attempts). At each planned height, the suspended capsule was remotely released, and its movement was captured using a conventional mobile phone. The recordings were taken against the backdrop of the modular structure, serving as a reference mesh, on the facade of the IPPT PAN building. Three selected snapshots captured during the test drop from a height of 25 m are shown in Fig. 9, depicting the initial position before releasing the capsule, the mid-flight stage, and the aftermath of touchdown. The corresponding velocities obtained from the tests are presented in Fig. 10. The maximum velocity components recorded during the drop tests are summarized in Table 1.

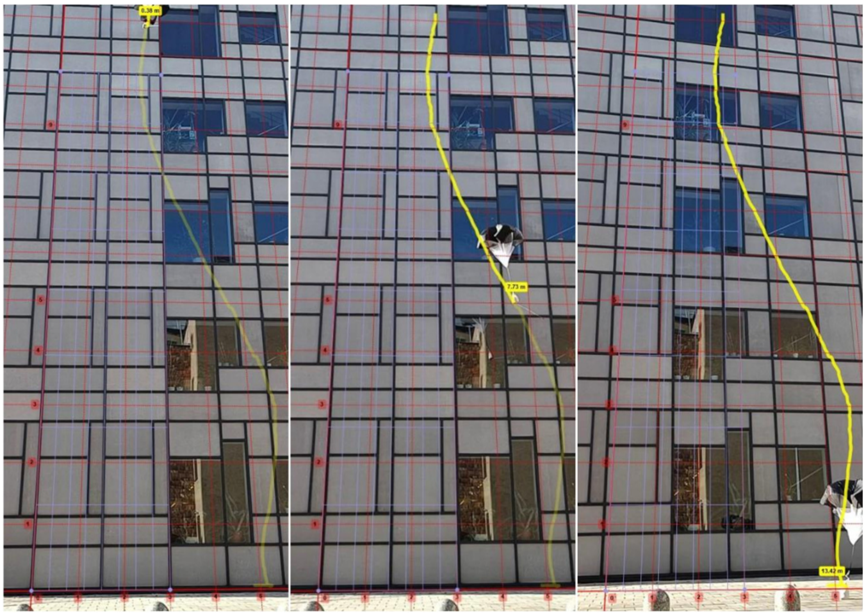

Figure 9. Highlighted snapshots showcasing the trajectory of the device during free fall from a height of 25 m.

The recorded images were analyzed using Kinovea software which was used to extract the kinematic data regarding the capsule motion. For each drop test, horizontal, vertical, and total velocities were determined. The analysis assumed two key conditions: (a) the movement of the load occurs within the designated vertical plane, and (b) the recording camera remains stationary relative to the chosen reference system. These conditions facilitated the accurate determination of the results.

The tests conducted from lower heights (4m and 8m) displayed a systematic but irregular rise in the total descent velocity, reaching approximately 5 m/s (4m) and 7 m/s (8m) respectively. In both cases, there was a noticeable increase in speed just before the contact with the ground. However, Table 1 demonstrates that the descent speeds stabilized below 9m/s for the drop test conducted from a height of 25 m.

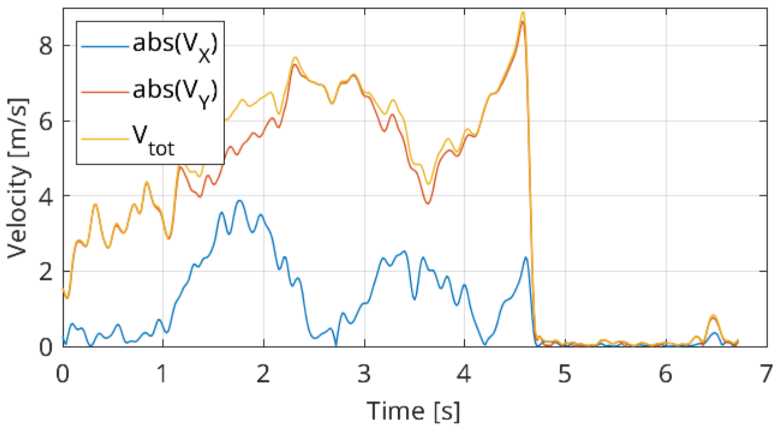

Figure 10. Velocities calculated for the drop tests conducted from a height of 25 m.

Table 1. Velocities obtained from drop tests.

Max. velocity [m/s]	Height of test drop				
	4m	8m	25m	25m	25m
Horizontal	2.60	2.15	3.06	2.59	3.88
Vertical	4.09	6.81	7.05	8.31	8.64
Total	4.74	7.12	7.48	8.50	8.88

5. CONCLUSIONS

Safety systems incorporating airbags for passenger protection have been used in the automotive industry since the 1970s. Currently, new solutions based on external airbag systems are being developed for protection of vehicles and pedestrians during road collisions. The systems for energy dissipation presented in this paper constitute a continuation of this technical concept, but tailored to the aviation industry. Although these solutions are at various stages of development, they reveal a high potential for practical implementation.

The first proposed system is AdBag, an external airbag designed specifically for drones, which are often equipped with specialized and expensive measurement devices. Protecting such flying objects is of great interest to both operators and manufacturers of these devices. Conversely, in the case of ultralight aircrafts the application of a safety system is oriented not only towards safeguard of the structure but also towards protection of human life, which constitutes a compelling rationale for their implementation. On the other hand, incorporating new systems in aviation is subjected to rigorous industry procedures and requires holistic testing to confirm their reliable operation. The final developed solution is an aidrop capsule, which can be successfully applied in rapid delivery of critical and life-saving payloads in emergency situations, such as food in disaster-stricken areas or medications during rescue missions in high-altitude regions. A wide range of conducted research, encompassing both numerical, laboratory, and field studies, contributes significantly to the development of new airbag-based safety systems for general aviation.

ACKNOWLEDGMENTS

The article was prepared with the support of the projects "Adaptive airbags for unmanned aerial vehicles emergency landing (ADBAG)" co-financed from the European Regional Development Fund within the Operational Programme Smart Growth 2014-2020, POIR.01.02.00-00-0083/16 and the project "SOFTLAND – Airbag system for increasing the small aircraft safety during emergency landing", E113407. The authors acknowledge the support of the National Centre for Research and Development and the National Science Centre, Poland, granted in the framework of the TANGO 4 programme (project TANGO-IV-C/0001/2019-00). The support of the National Science Centre, Poland, granted through the Agreement 2018/31/D/ST8/03178 is gratefully acknowledged.

REFERENCES

[1] J. Holnicki-Szulc, Ed., Smart technologies for safety engineering, Wiley, 2008.

[2] J. Holnicki-Szulc, C. Graczykowski C., G. Mikułowski, A. Mróz and P. Pawłowski, Smart Technologies for Adaptive Impact Absorption, Solid State Phenomena, 154, pp. 187-194, 2009.
[3] J. Holnicki-Szulc, C. Graczykowski, G. Mikulowski, A. Mroz, P. Pawlowski, R. Wiszowaty, Adaptive impact absorption - the concept and potential applications, International Journal of Protective Structures, vol. 6(2), pp. 357-377, 2015.
[4] K. Sekuła, C. Graczykowski, J. Holnicki-Szulc, On-line impact load identification, Shock and Vibration, vol. 20(1), pp. 123-14, 2013
[5] Z. Wołejsza, J. Holnicki-Szulc, C. Graczykowski, K. Hinc, R. Faraj, T. Kowalski, G. Mikułowski, K. Kaźmierczak, R. Wiszowaty, P. Pawłowski, Dynamics and control of adaptive airbags for UAV impact protection, ISMA 2018 / USD 2018, International Conference on Noise and Vibration Engineering 2018-09-17/09-19, Leuven (BE), pp.3661-3670, 2018
[6] J. Warrick, C. Lee, "Advanced airbag system for cargo airdrop", 16th AIAA Aerodynamic Decelerator Systems Technology Conf. and Seminar, Boston, USA, 2001, pp. 293-303
[7] J. Richert, D. Coutellier, C. Götz, W. Eberle, "Advanced smart airbags: The solution for real-life safety?", Int. J. Crashworthiness, vol. 12, pp. 159-171, 2007
[8] G. Mikułowski, R. Wiszowaty, Pneumatic Adaptive Absorber: Mathematical Modelling with Experimental Verification, Mathematical Problems in Engineering, ISSN: 1024-123X, vol.2016, pp.7074206-1-14, 2016
[9] R. Faraj, G. Mikułowski, R. Wiszowaty, Study on the state-dependent path-tracking for smart pneumatic shock-absorber, Smart materials and Structures, ISSN: 0964-1726, vol.29(11), pp.115008-1-25, 2020
[10] L. Knap, M. Makowski, K. Siczek, P. Kubiak, A. Mrowicki, Hydraulic Vehicle Damper Controlled by Piezoelectric Valve, Sensors, 23 (4), art. no. 2007, 2023
[11] P. Pawłowski, M. Ostrowski, C. Graczykowski, High performance valves for adaptive inflatable structures with flow driven control, 6th Eccomas Thematic Conference On Smart Structures And Materials, 2013-09-03/09-06, Torino (IT), pp.1-10
[12] R. Faraj, C. Graczykowski, J. Holnicki-Szulc, Adaptable pneumatic shock absorber, Journal of vibration and Control, ISSN: 1077-5463, vol.25(3), pp.711-721, 2019
[13] M. Fanton, H.V. Alizadeh, A. Domel, M. Devlin, M. Kurt, G.M. Mungal, D.B. Camarilo, E. Hawkes, "Variable area, constant force shock absorption motivated by traumatic brain injury prevention", Smart Mater. Struct., vol. 29(8), 085023, 2020
[14] R. Faraj, B. Popławski, D. Gabryel, T. Kowalski, K. Hinc, Adaptive airbag system for increased evacuation safety, Engineering Structures, ISSN: 0141-0296, vol.270, pp.114853-1-5, 2022
[15] T. Kowalski, R. Faraj, C. Graczykowski, K. Hinc, G. Mikułowski, P. Pawłowski, Z. Wołejsza, Development of adaptive airbags for emergency landing of small uav, SolMech 2018, 41st Solid Mechanics Conference, 2018-08-27/08-31, Warszawa (PL), pp.1-2, 2018